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Simulation of a Mosaic Sensor System

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Final Report

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This report discusses a mosaic sensor system simulation program (MSSP) that has been developed at The Aerospace Corporation. The MSSP program is a viable tool for the evaluation of a variety of mosaic sensor concepts.

The idea of using a mosaic array to represent an image is an old one. Sensors constructed from the mosaic concept have the advantage of simplicity. Theoretically the image information may be instantaneously obtained from the outputs of all the detector cells in the mosaic array, thus eliminating the time → next page

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delay problem inherent in a scanning-type sensor. A mosaic sensor system is often more reliable than a scanning sensor system because there are a minimum of mechanical components susceptible to failure.

Typically, a mosaic focal plane consists of a large number of detector cells in order to produce fine image resolution. Digital simulation of a mosaic sensor system requires a considerable amount of repetitive calculations because of the large number of cells. It is very important to design a mosaic sensor simulation program with computation algorithms that are highly efficient in order to minimize the run time of the computer.

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CONTENTS

FIGURES

FIGURES (Continued)

INTRODUCTION

This paper describes the approach and results of a mosaic sensor simulation program (MSSP) developed at The Aerospace Corporation. Currently, both scanning and staring IR sensors are of interest. A scanning sensor usually contains one or more rows of detector cells which scan back and forth in order to cover the field of view (FOV). A staring sensor usually contains a mosaic array of detector cells. In order to cover the FOV with sufficient resolution, the mosaic array may contain a very large number of cells, typically on the order of 10^6 or more.

For certain applications, the mosaic sensor system has an advantage over the scanning sensor. The mosaic sensor is particularly useful for the separation of a moving target from a highly emissive but stationary background. The background may be effectively removed by analog filtering or by frame-to-frame subtraction (numerical differentiation) since it contributes only to DC outputs from the detector cells. These types of processing, however, transform the target's intensity amplitude information into cell edge-crossing information. This leads to a variety of detector cell designs which include "reticles," and an alternate biasing scheme which is sometimes called a "push-pull" detector (in order to distinguish it from the regular "single-ended" detector). Figure 1 illustrates some typical designs of mosaic detectors (Ref. 1).

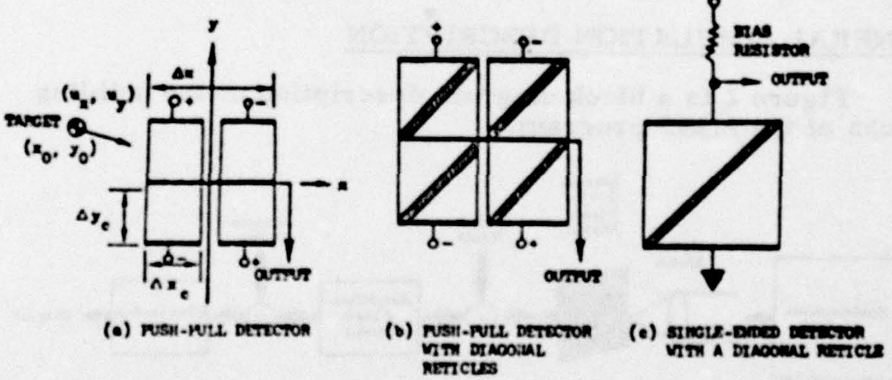


Figure 1. Typical Mosaic IR Detectors

Since the focal plane consists of many detectors, computational efficiency is an important consideration in digital simulation of a mosaic sensor. A large number of repetitive calculations is often required to process the detector outputs. To take advantage of the fact that all detector cells (or at least groups of them) have identical characteristics, Winter (Refs. 2, 3, 4) has introduced the table look-up approach, which can greatly reduce the computational load for both point sources and extended sources. Winter's table look-up approach has been adopted for fast calculation of the point spread function response. With this approach, the point spread function description does not need to be analytic and may be given in the form of a numerical table. For any given detector cell design, a table of cell response is set up in a preliminary routine which is stored in the form of a matrix. For a given target location in the center cell, the set of outputs of the m x n cells which include the given cell are calculated and stored. The integers m and n are determined by the optics point spread function and the dimensions of the detector. Zero outputs are assumed for cells outside the m x n block. Numerical convolution is used to calculate the amplifier/filter response in time domain.

A general description of the MSSP simulation is given below. The modeling techniques on targets, backgrounds, optics, focal planes, and filters are discussed in detail in the third section. More specific discussions on the simulation program, some typical outputs, and a conclusion are given in subsequent sections.

GENERAL SIMULATION DESCRIPTION

Figure 2 is a block diagram description of the building blocks of the MSSP program.

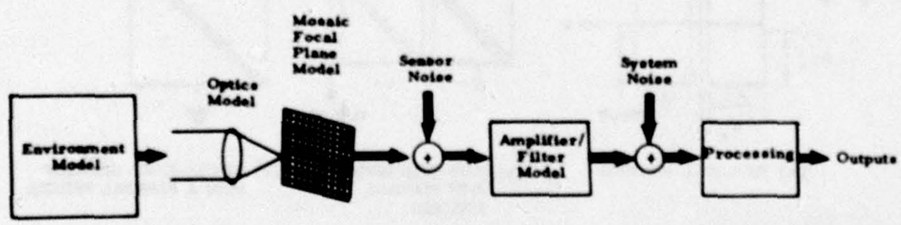


Figure 2. Mosaic Sensor System Simulation Block Diagram

The driver unit, called the environmental model, consists of ingredients that are necessary to generate a mosaic image. In MSSP, it has a target trajectory model and a background model.

The outputs of the environmental model are the inputs of the optics model. The transmission attenuation, the spectral filtering, and the lens degradation of the image are modeled. The optical blurring is characterized by a point spread function which is often approximated by a Gaussian function. In MSSP, either a Gaussian function or a tabulated function may be realized. There is no significant difference in run time in either case, since Winter's table look-up approach has been used so that there is no need to calculate repetitively the point spread response.

The mosaic focal plane model evaluates the output of each detector cell given the location of the center of the target and its intensity. A discrete spatial convolution method is often used to evaluate contribution of an extended source which arises from background modeling. However, a point-source discretization technique is used for this simulation program. Detector noise is injected at the cell outputs.

The output of each detector is passed through an amplifier/filter. The filter is either a matched filter which approximately matches the expected target signal waveform (in order to maximize the signal-to-noise ratio), or just an AC amplifier with sufficient bandwidth to cover the signal bandwidth. The DC component of the cell output which is due mainly to the interfering background is removed by the AC amplifier. Sometimes this process is carried out by some form of numerical differentiation which is called "frame-to-frame subtraction." In MSSP, the amplifier/filter is realized by numerical convolution. System noise is also added at the output of each amplifier/filter.

MODELING TECHNIQUES

1. Environmental Model

In the current version of MSSP, the environmental model consists of a moving target model and a background model.

a. Moving Target Model

The motion and intensity profile of a moving target is described by a set of three N^{th} order polynomials. Let x_j and y_j be the focal plane position of target j. Let I_j be the intensity. Then

$$x_j(t) = \sum_{k=0}^{N} a_{jk}\left(t - t_{0j}\right)^k \qquad \text{(focal plane unit)}$$

$$y_j(t) = \sum_{k=0}^{N} b_{jk}\left(t - t_{0j}\right)^k \qquad \text{(focal plane unit)}$$

$$I_j(t) = \sum_{k=0}^{N} c_{jk}\left(t - t_{0j}\right)^k \qquad \text{(watts/sr)}$$

where t_{0j} is the reference time for target j. The inertial motion of a target is first simulated by a separate trajectory simulation program; the same program also provides the inertial attitude of the sensor. The motion of the target on the focal plane is obtained by projecting the inertial motion along the sensor's line of sight (LOS) into the sensor coordinate frame, then scaling by the ratio of the focal length to the range from the sensor to the target. Least-squares fit is then performed to determine the polynomial coefficients.

b. <u>Background Model</u>

Random step-function models have been widely used as statistical models for background irradiance (Refs. 5, 6). This type of model is adopted for MSSP. More explicitly, the background process is characterized by

$$B(x, y) = \sum_m \sum_n a_{mn} \left[u(x - x_m) - u(x - x_{m+1})\right] \bullet \left[u(y - y_n) - u(y - y_{n+1})\right]$$

where $u(\bullet)$ denotes the unit-step function.

The jump points x_m and y_n are characterized by two exponential processes, i.e., the probability of having a new jump is given by

$$P(\text{jump at } x > x_m \mid x_m \text{ is the last jump}) = 1 - e^{-\lambda(x - x_m)}$$

$$P(\text{jump at } y > y_n \mid y_n \text{ is the last jump}) = 1 - e^{-\lambda(y - y_n)}$$

where $1/\lambda$ is the mean distance between jumps.

The amplitude a_{mn} is a non-negative random process in m and n. The Rayleigh distribution is chosen as a model for a_{mn}.

Spatially, the intensity is assumed to be exponentially correlated. For any m, n, j, k, we have the relationship

$$E\{[a_{mn} - E(a_{mn})][a_{jk} - E(a_{jk})]\} = \sigma_s^2 e^{-\alpha_s(|m-j|+|n-k|)}$$

where σ_s and α_s are constants characterizing the background correlation.

The above model is an adequate description for a stationary background. For a non-stationary background (a_{mn}, x_m, y_n) are also random processes in time. In MSSP, (x_m, y_n) are assumed to be independent of time and a_{mn} is exponentially time correlated, i.e.,

$$E\{[a_{mn}(t_1) - E(a_{mn}(t_1))][a_{mn}(t_2) - E(a_{mn}(t_2))]\} = \sigma_t^2 e^{-\alpha_t|t_2-t_1|}$$

where σ_t and α_t are constants characterizing the time correlation.

With this approach, computational efficiency is high since the background scenario needs to be generated only once. The subsequent time fluctuations of a_{mn} are then added in a random fashion.

A typical background scenario is illustrated in Figure 3.

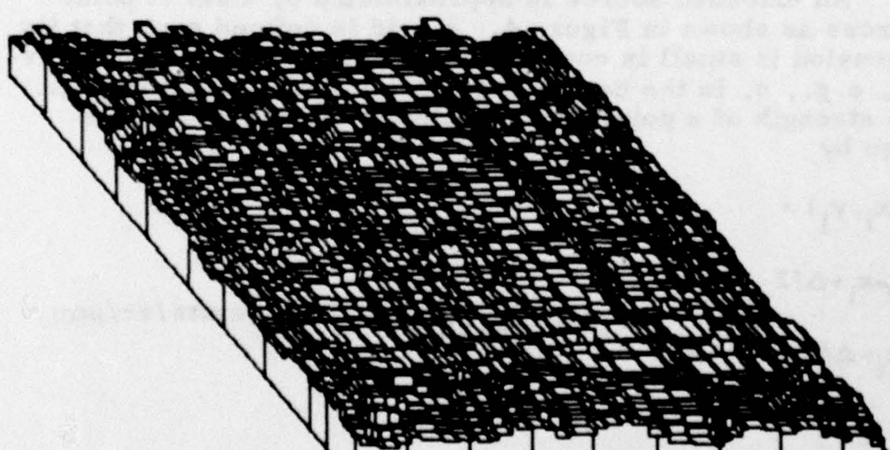


Figure 3. A Typical Simulated Background Scenario

2. Optics Model

The radiated power of a point source is modeled by

$$dP = p_P \, d\Omega \, d\lambda \qquad \text{(watts)}$$

where

p_P = the power density of the point source in watts/sr/μm

Ω = solid angle in steradians

λ = spectral wavelength in micrometers

The background structure has been modeled as an extended source. The power radiated over the surface is modeled by

$$dP = p_E \underline{n}_{LOS} \cdot \underline{n} \, ds \, d\Omega \, d\lambda \qquad \text{(watts)}$$

where

p_E = watts/m^2/sr/μm is the power density of the extended source

$\underline{n}_{LOS}$ = the unit vector from the differential area ds to the sensor, and $\underline{n}$ is the unit normal to ds.

An extended source is approximated by a set of point sources as shown in Figure 4. A grid is defined such that its dimension is small in comparison with the point spread coverage, e.g., σ, in the case of a Gaussian point spread model. The strength of a point source which is located $a(x_i, y_j)$ is given by

$$p_P(x_i, y_j) =$$

$$\int_{x_i-\Delta/2}^{x_i+\Delta/2} \int_{y_j-\Delta/2}^{y_j+\Delta/2} p_E(x, y)(\underline{n}_{LOS} \cdot \underline{n}) \, dx \, dy \qquad \text{(watts/sr/μm)}$$

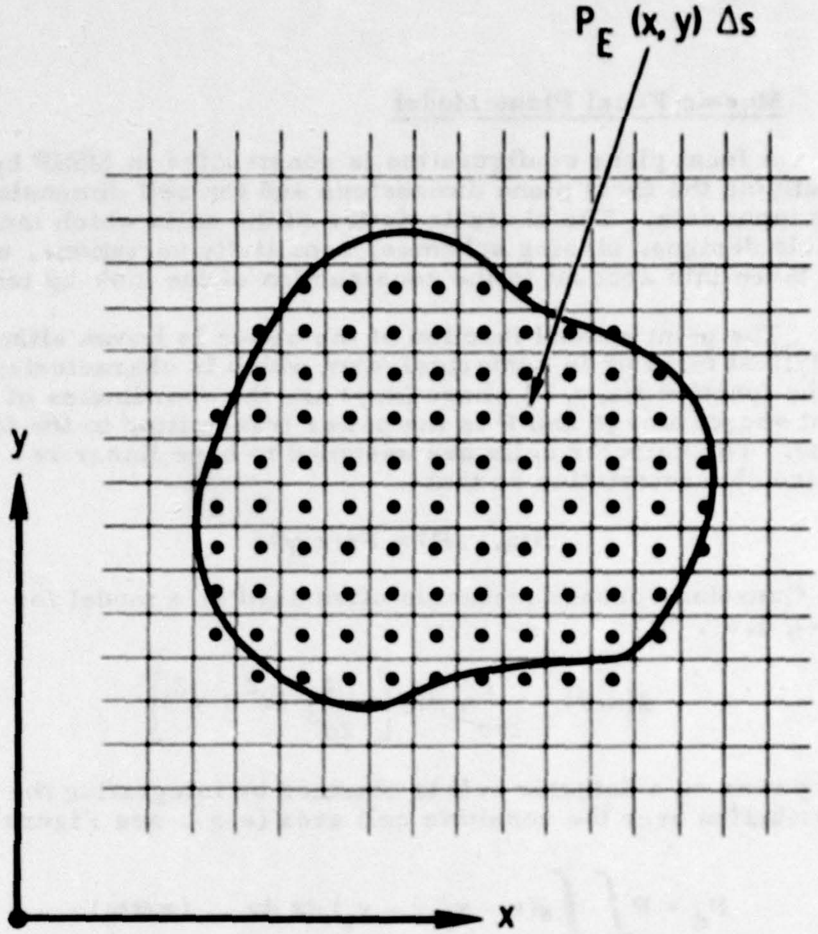


Figure 4. Discretization of an Extended Source

where Δ is the grid dimension. With this approach, only point sources are involved in the calculations of the cell outputs. For each point source, the power transmitted to the focal plane is given by the expression

$$P_f = \eta p_P \frac{A}{R^2} \Delta\lambda \qquad \text{(watts)}$$

where

- η **= optical transmission efficiency**
- **A = aperture area**
- **R = range from sensor to source**
- $\Delta\lambda$ **= spectral bandwidth**

3. Mosaic Focal Plane Model

A focal plane configuration is constructed in MSSP by specifying the focal plane dimensions and the cell dimensions with input data. The characteristics of the cells which include reticle designs, biasing schemes, sensitivity variations, etc. are taken into account in the construction of the look-up table.

The point spread function of the optics is known either in analytical form or in numerical form which is characterized by the function f(x, y, P) where (x, y) are the coordinates of the point source image and P is the power transmitted to the focal plane. The detector cells are assumed to have linear response characteristics so that

$$f(x, y, P) = Pg(x, y)$$

The Gaussian spread function is often used as a model for $g(\bullet, \bullet)$, i.e.,

$$g(x, y) = \frac{1}{2\pi\sigma^2} \exp\left[-\frac{1}{2\sigma^2}(x^2 + y^2)\right]$$

The power on a detector cell is obtained by integrating the contribution over the sensitive cell area (e.g., see Figure 5)

$$P_d = P \iint_{A_c} g(x - x_t, y - y_t)\, dx\, dy \qquad \text{(watts)}$$

where (x_t, y_t) are the coordinates of the point target image, and P is the power transmitted to the focal plane by the point source. The integral portion of the above expression is obtained readily by table look-up. The (static) output voltage of the cell is obtained by multiplying the P_d by cell's (static) responsivity R_c, i.e.,

$$v_d = R_c P_d \qquad \text{(volts)}$$

where R_c is in volts/watt.*

The dynamic behavior of the cell is considered as a part of the amplifier/filter module which will be discussed later.

---

*Sometimes the outputs are in amperes; in this case R is in amp/watt.

For a rectangular cell without reticles and assuming a circular Gaussian point spread function, v_d may be expressed in terms of error functions as

$$v_d = \frac{PR_c}{4}\left\{\mathrm{erf}\left[\frac{1}{\sqrt{2}\sigma}\left(x_c + \frac{W}{2} - x_t\right)\right] - \mathrm{erf}\left[\frac{1}{\sqrt{2}\sigma}\left(x_c - \frac{W}{2} - x_t\right)\right]\right\}$$

$$\bullet\ \mathrm{erf}\left\{\left[\frac{1}{\sqrt{2}\sigma}\left(y_c + \frac{L}{2} - y_t\right)\right] - \mathrm{erf}\left[\frac{1}{\sqrt{2}\sigma}\left(y_c - \frac{L}{2} - y_t\right)\right]\right\}$$

where (x_c, y_c) is the location of the center of the cell and W and L are respectively the width (along x) and the length (along y) of the cell. Here erf $(\bullet)$ is defined by

$$\mathrm{erf}(\xi) = \frac{2}{\sqrt{\pi}}\int_0^{\xi} e^{-t^2}\, dt$$

An illustration of cell response calculation is shown in Figure 5.

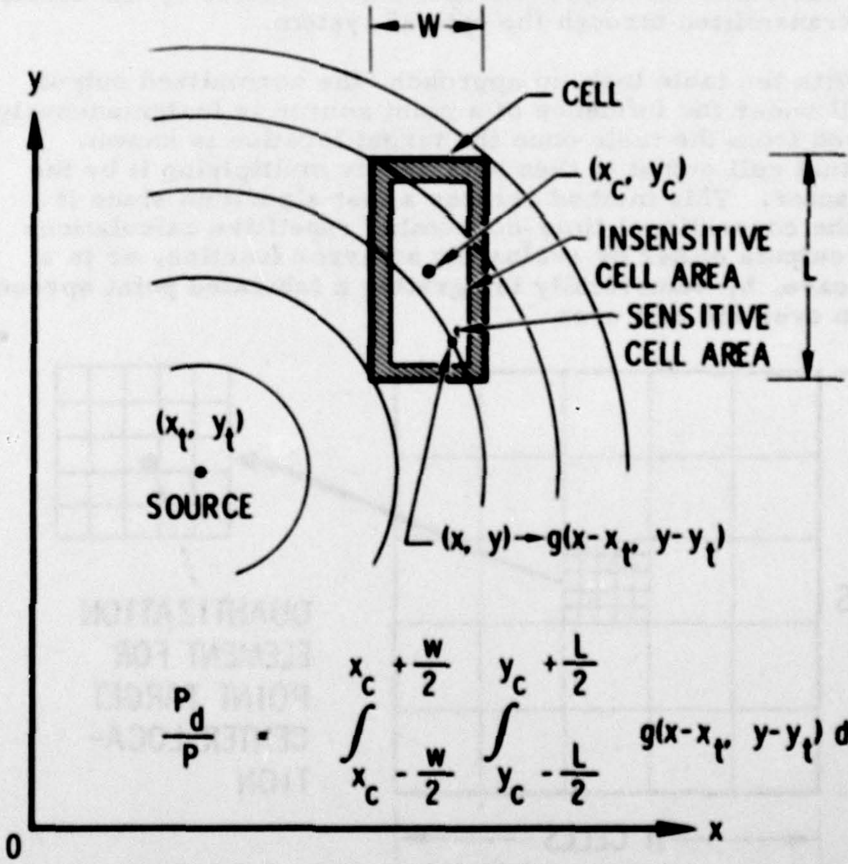


Figure 5. Calculation of Cell Output Due to a Point Source Influence

In order to construct a look-up table using Winter's approach, the point target location on a cell is quantized (see Figure 6); i.e., if the target is included in the i j^{th} quantization element, it is assumed to be located at its center. Only m x n neighboring cells are considered in the table. The choice of integers m and n depends on the extent of coverage of the point spread function. The cells beyond this group are assumed to have negligible outputs for the given point target location. The table values are calculated assuming a power of one watt transmitted through the optics. Figure 6 shows the cell block structure for the construction of a look-up table. The target is located somewhere in the center cell which falls into one of the small quantization grid elements. For the given (normalized) point spread function, the outputs of all the cells in the block are calculated for target location at the center of every quantization element. The results are stored in the look-up table. Thus, T(i, j, k, l) is the output of cell (k, l) to a target at (i, j). In actual calculation of a cell output, the value obtained from the table is scaled by the actual power transmitted through the optical system.

With the table look-up approach, the normalized output of a cell under the influence of a point source is instantaneously retrieved from the table once the target location is known. The actual cell output is then obtained by multiplying it by the scale factor. This method creates a fast algorithm since it omits the conventional time-consuming repetitive calculations of cell outputs either by evaluating an error function, or in a worse case, by numerically integrating a tabulated point spread function over the cell area.

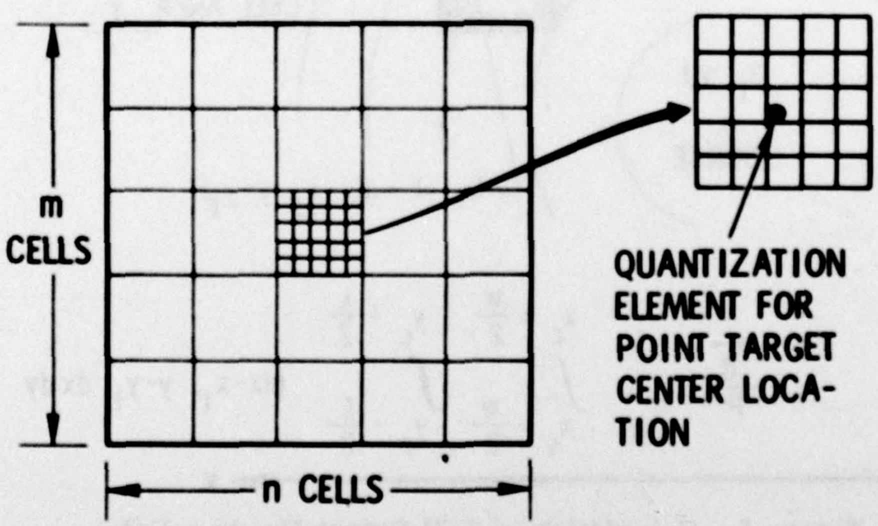


Figure 6. Look-up Table Structure

4. Amplifier/Filter Model

The amplifier/filters for shaping the detector cell outputs are usually a linear device, possibly with a large bandwidth in comparison with that of the target signal waveform. We shall assume that an amplifier provides only a pure gain, and the shaping of the signal waveform takes place in the filter. Furthermore, the detector cell dynamics are also assumed to be part of the filter in our simulation approach. It is implemented as an additional filter structure. Since the amplifier only contributes to the scale factor, we need only discuss the filter in greater detail.

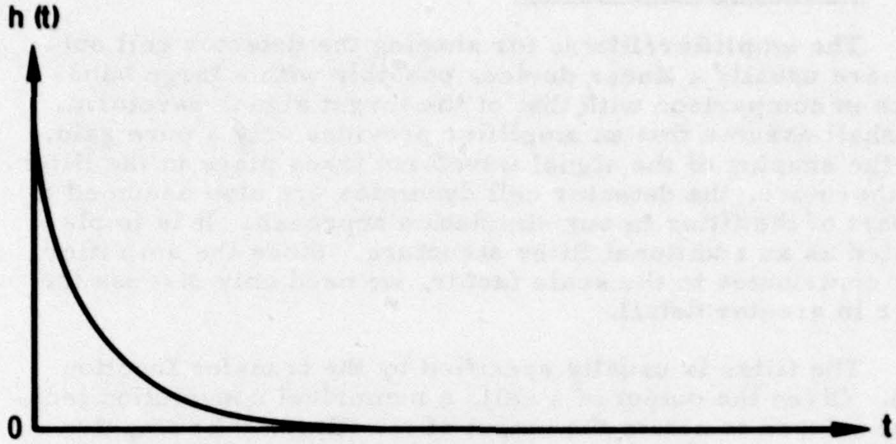
The filter is usually specified by the transfer function $H(s)$. Given the output of a cell, a numerical convolution technique is used to obtain the output of the filter. The impulse response $h(t)$, which is the inverse Laplace transform of $H(s)$, is discretized to obtain the unit sample response by integrating it over the sampling period, yielding the set of numerical values $\{h_i\}$.

In a DC filter, $\{h_i\}$ can usually be approximated by taking a limited number of terms. If $h_i \simeq 0$ for $i > k$, then the output of the cell u_n is obtained by

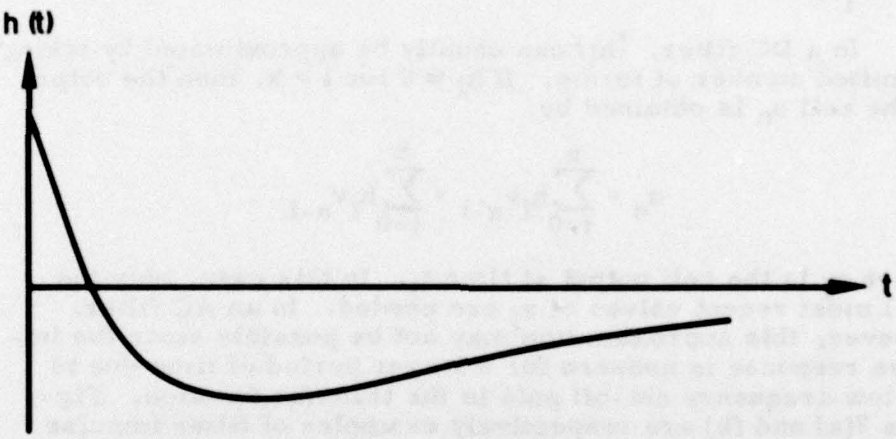
$$u_n = \sum_{i=0}^{n} h_i v_{n-i} = \sum_{i=0}^{k} h_i v_{n-i}$$

where v_j is the cell output at time t_j. In this case, only the $k + 1$ most recent values of v_j are needed. In an AC filter, however, this approximation may not be possible since the impulse response is nonzero for a longer period of time due to the low-frequency cut-off pole in the transfer function. Figures 7(a) and (b) are respectively examples of filter impulse responses of a DC and AC filter.

Random noise sources are present within the detectors and the amplifier/filter system. Each noise source is modeled by a sequence of Gaussian random numbers with time correlation. The effect of time correlation is implemented by numerical convolution in the same manner as in the case of the filter. The transfer function is usually determined from a given noise power spectral density model. A first-order correlation profile is often adequate for the simulation purposes.



(a) DC FILTER IMPULSE RESPONSE



(b) AC FILTER IMPULSE RESPONSE

Figure 7. Typical Filter Impulse Response

SIMULATION STRUCTURE

The MSSP simulation is implemented on the CDC 7600 in Fortran IV. Figure 8 shows the essential elements in the MSSP program. Except for table look-ups and numerical convolutions, all calculations are carried out once only at the beginning of the program. The storage requirement is dictated by the number of cells in the focal plane and the number of required time-sampled outputs for each detector cell. For a large focal plane simulation, the outputs may be stored on a disc file (or tape) for plotting, or testing data processing algorithms. Figure 9(a) shows an example of a 10 cell by 10 cell simulated focal plane with a target traversing it diagonally. Figures 9(b) through 9 (d) are typical outputs from a given detector cell at different stages of the sensor system.

CONCLUSIONS

A general-purpose mosaic sensor Fortran IV simulation program called MSSP has been developed. This program is flexible enough that most of the parameters, including the description of the focal plane structure, are controlled by external namelist inputs. The program is modularized so that modifications can be made on each module without disturbing the remaining structure of the program. The models discussed in this paper are implemented as subroutines in the program. The table look-up approach undoubtedly results in great savings in computational effort, since it bypasses the routine but painful repetitive calculations of the point spread function response for a finite and possibly irregular sensitive cell area. No specific timing comparison was attempted bebetween the conventional "brute-force" approach and the table look-up approach. The MSSP program, however, is designed computationally to be as efficient as possible, as a general tool for the evaluation of various mosaic sensor concepts. For a large number of detector cells with a long time history, online computer storage may not be enough even with large-core memory storage. A solution to this problem is to calculate and store the data only on the cells of interest. Another solution is to use external disc storage and manipulate the data by means of random access techniques. The latter approach is necessary if the output data is being used for the evaluation of target detection and tracking algorithms.

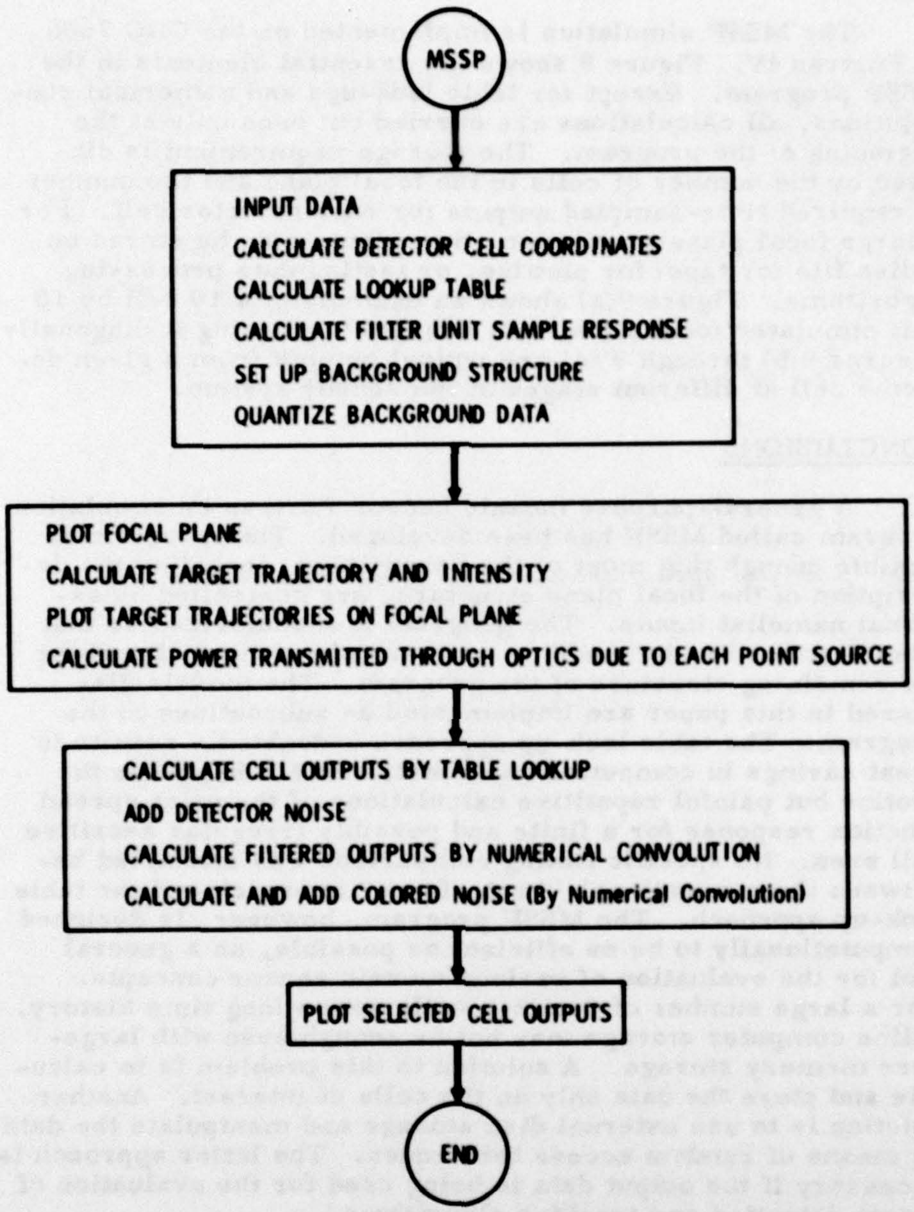


Figure 8. MSSP Simulation Logic Flow Diagram

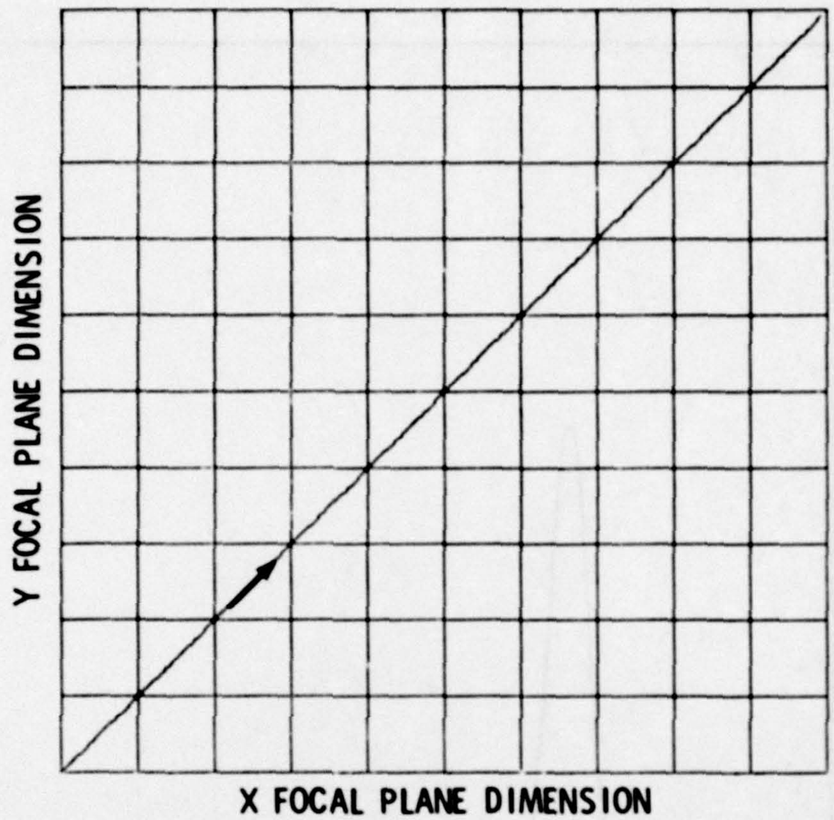


Figure 9(a). An Example of Focal Plane Trajectory Plot

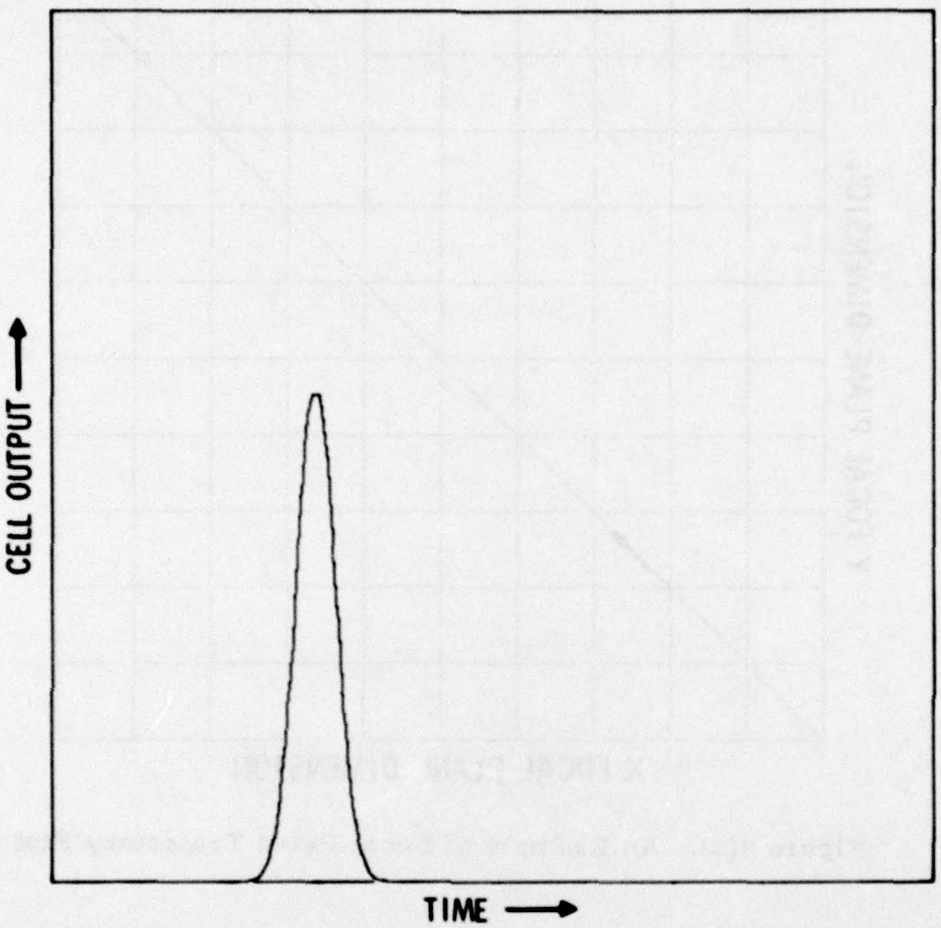


Figure 9(b). A Sample Output of a Detector Cell

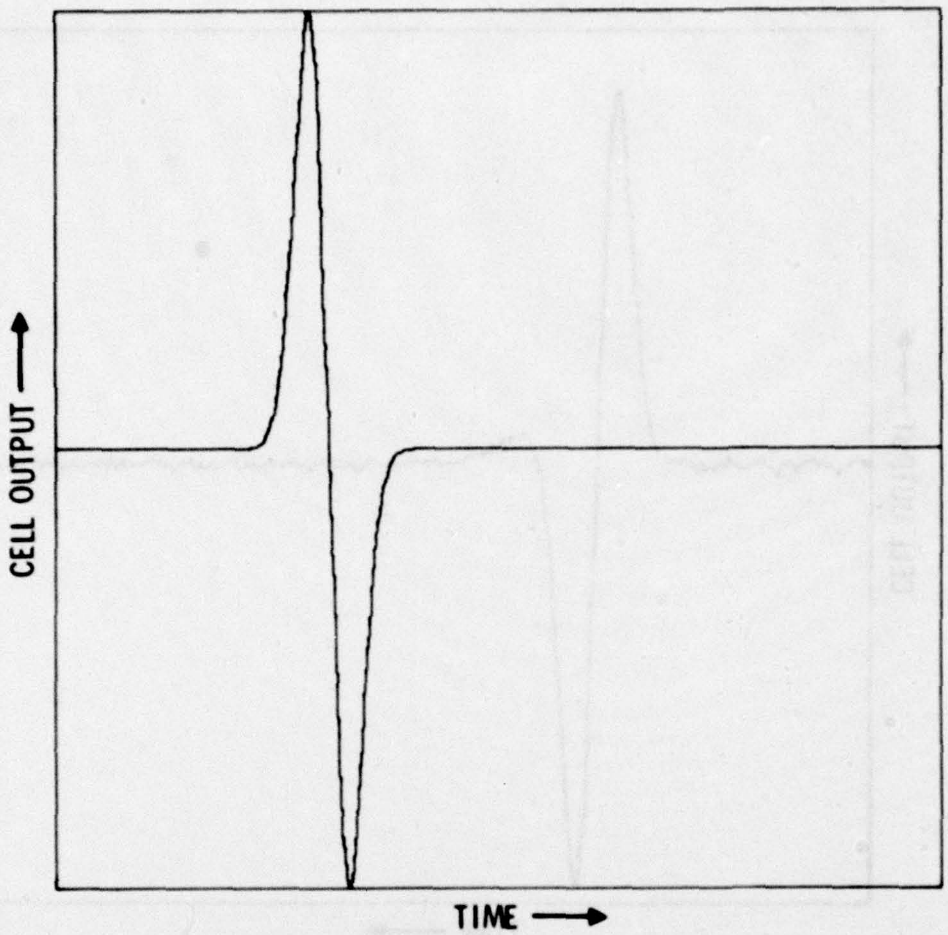


Figure 9(c). Output of the Same Cell After Numerical Differencing

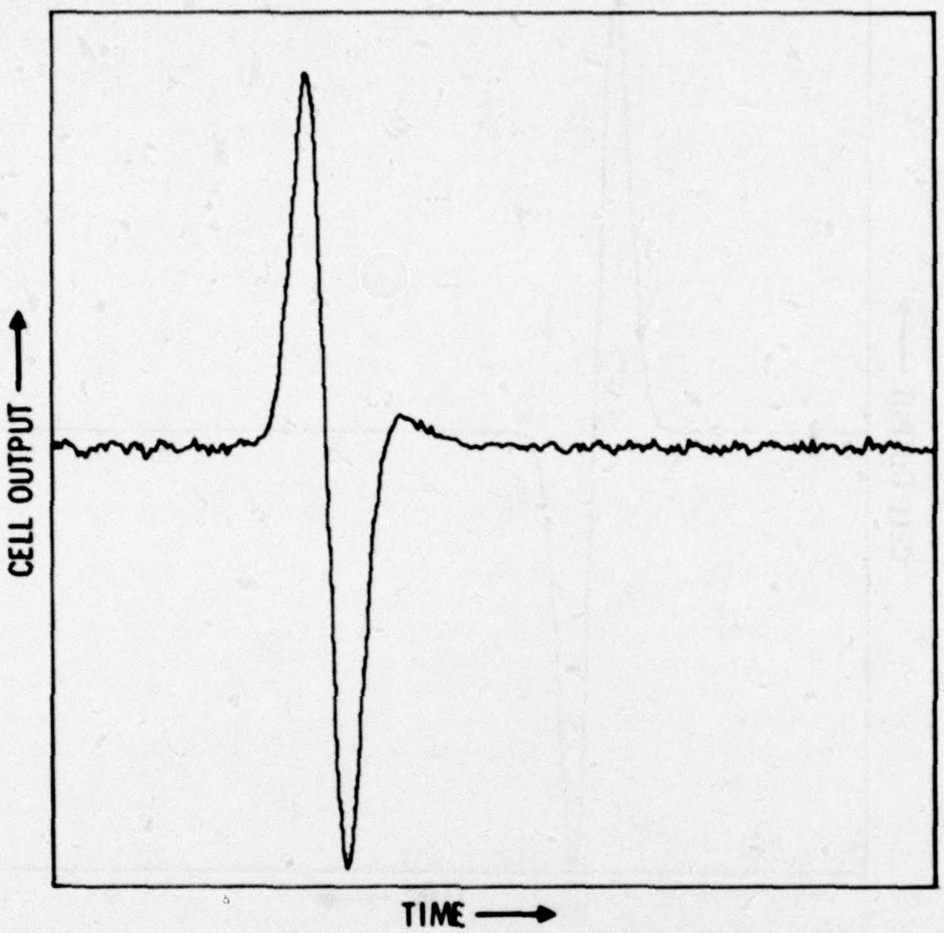


Figure 9(d). Filtered Output With Noise

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